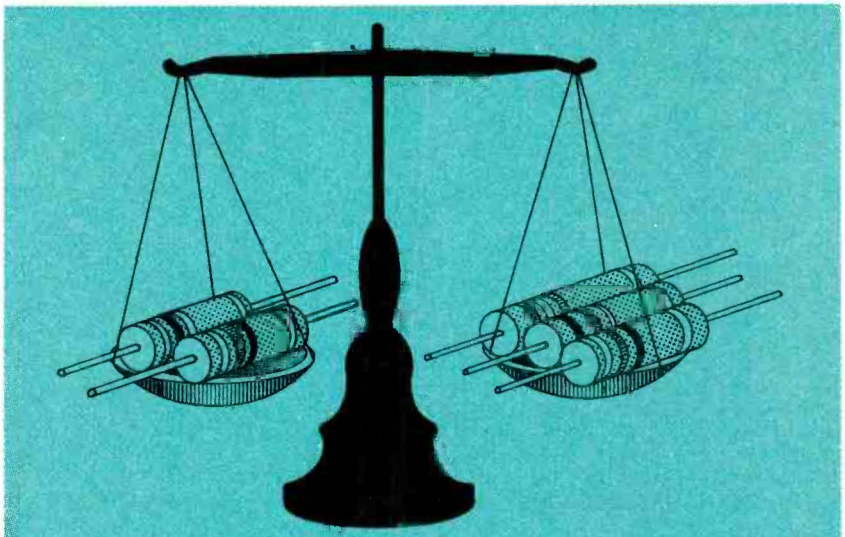
RAY MARSTON



BRIDGES: Matching Resistors and Capacitors

Learn about special resistance and capacitance bridges and substitution boxes.

THIS THIRD ARTICLE IN A SERIES ON measurement bridges is about special bridges that might not be known to all readers. However, the article includes schematics building some of these resistance-matching and ratio-matching bridges. They will give you an opportunity to learn about those bridges and then, after you build the circuits, you can match or duplicate resistors within a tolerance of ±0.003%.

The first part of this series discussed the Wheatstone resistance-measuring bridge and its derivatives, and the second part explained precision inductance, capacitance and resistance (LCR) bridges including the Maxwell and Hay AC bridges.

In addition to the DC and low-frequency AC bridges described in the two previous articles, there are three others that should be of value to experimenters and hobbyists. The first of these is the *transformer ratio-arm bridge*. Fig. 1 is the basic schematic for this bridge. The value of the ratio arms of this bridge (shown as switch-selectable at 0.1/1, 1.0/1, or 10.0/1 in Fig. 1) depends entirely on transformer T1's turns-ratios. Suitable transformers can be wound with a precision better than 0.01%.

The value of an unknown impedance Z_X can be balanced against that of a standard impedance Z_S either by varying the value of the standard or the value of the ratio arms. Resistors or capacitors can be balanced against each other by placing them on opposite sides of the bridge, as shown. In addition, a capacitor can be balanced against an inductance by placing both components on the same arm of the bridge.

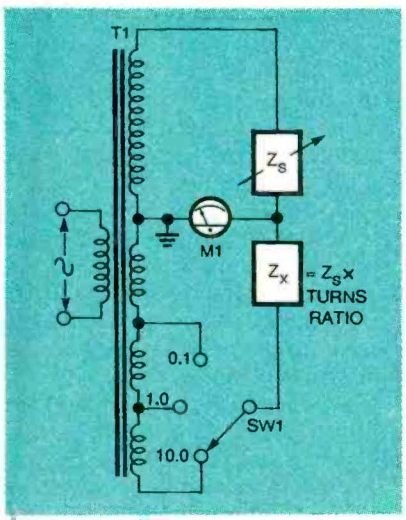


FIG. 1—A SCHEMATIC FOR a transformer ratio-arm bridge.

The *DC resistance-matching bridge*, shown in Fig. 2 is another important bridge. This simple circuit permits resistors to be matched to within ±0.1% or better. This bridge is based on two basic principles: (1) If R_A and R_B are equal, the value of R_{MATCH} will equal that of R_S at balance; (2) If R_A and R_B are equal, they will generate the same output voltage, regardless of the way they are connected across the power supply.

With the second principle in mind, R_A and R_B are joined by a 500-ohm potentiometer and they are connected to the DC supply through the biased polarity-reversal switch S1.

To measure with this resistance-matching bridge, connect R_S and R_{MATCH} in the locations shown. Notice that R_{MATCH} is shown simply as a fixed resistor (R_{M1}) in series with a variable resistor (R_{M2}). With the DC supply connected, a meter reading can now be taken. If necessary, trim R_{M2} and R3 to make this reading a reasonable value. Repeatedly toggle switch S1 and trim R3 until identical meter readings appear in both toggle positions. That completes the adjustment.

Trim the value of R_{MATCH} with R_{M2} to zero the meter reading. When it is zeroed, R_S and R_{MATCH} are matched. After R3 has been initially set, it should rarely require adjustment. The circuit's matching fidelity is limited to ±0.1% by the balance-detection meter's sensitivity.

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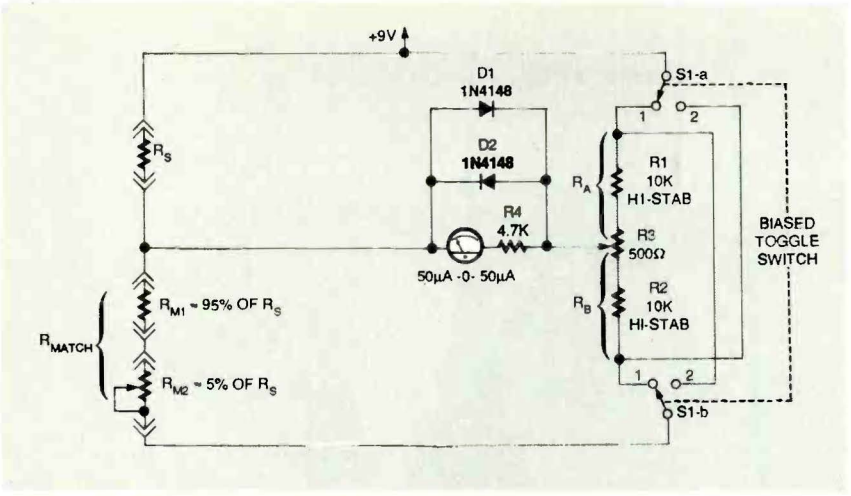

FIG. 2—THIS RESISTANCE-MATCHING bridge will match resistors within ±0.1%.

TABLE 1—CHARACTERISTICS OF RESISTORS

Resistor Type	Resistance Range (Ohms)	Tolerance Range (Percent)	Temperature Coefficient ppm/°C
Carbon comp.	1 - 100 M	± 5 - ± 20	±100 - ±1000
Carbon film	1 - 200 M	±0.5 - ±10	–800 - +200
Metal film	0.27 - 100 M	±0.01 - ±2	±3 - ±200
Cermet film	10 - 500 M	±0.05 - ±5	±50 - ±200
Wirewound			
Precision	0.001 - 60 M	±0.001 - ±1	±0.5 - ±50
Power	0.1 - 1 M	±1 - ±10	±20 - ±450

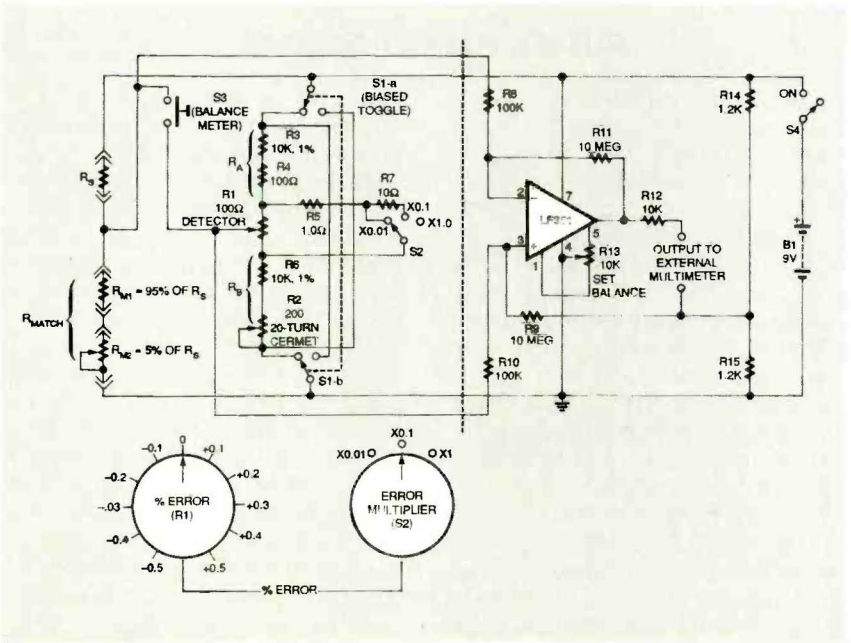

FIG. 3—THIS HIGH-PRECISION RESISTANCE-matching bridge will match resistors to within ±0.003%.

When building a resistance-matching bridge or when matching resistors, install only resistors whose resistive elements have low-temperature-coefficients measured in parts per million per degree Celsius (ppm/°C). Do not touch or handle those resistors while balancing or matching values. Table 1 give values of coefficients of resistance for the common commercial resistive elements. These include carbon film, carbon composition, metal film, thick film, and wirewound.

When making measurements with the bridge, be aware that the R_{MATCH} value can be trimmed (to make it equal R_S) with a series resistor to increase its value or a shunt resistor to reduce it.

Resistance-matching bridge.

Figure 3 is the schematic for a precision resistance-matching bridge that includes a DC differential amplifier for driving the meter. It offers such high balance-detection sensitivity that resistors can be matched to within ±0.003%. This bridge also has the ability to indicate on potentiometer R1's calibrated scale, the percentage of the out-of-match error of R_{MATCH}. This scale spans ±0.5%, 0.05%, and 0.005% in three switch-selected ranges.

To set up the bridge initially, insert R_S and R_{MATCH} in their positions, connect operational amplifier IC1's output to an external multimeter, and connect the power supply through switch S4. Then close momentary pushbutton switch S3 and trim IC1's SET BALANCE control R13 to obtain a zero reading on the meter's most sensitive DC current range. Then release switch S3.

Now set potentiometer R1 at midscale and, with S2 initially set to its ×1.0 scale, toggle S1. Trim potentiometer R2 (and if necessary, trimmer R_{M2}) to find a setting where the meter reading are identical in both toggle positions. As potentiometer R2 nears the balance point, increase the balance sensitivity with S2, until a perfect balance is obtained on the ×0.01 range. That completes the initial setup procedure.

Resistor R_{MATCH} can then be matched to R_S by trimming R_{M2} for a zero reading on the meter. After the circuit has been set as described, R2 and operational

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amplifier IC1's SET BALANCE control R13 should need adjustment only rarely. In all further matching operations, the following procedure can be followed, after verifying the correct meter and toggle balances.

Position R_S, R_{MATCH}, and the external multimeter. Turn switch S2 to the ×1.0 position, and switch the bridge on with switch S4. If R_{MATCH} is within ±0.5% of the R_S value, it should now be possible to set the bridge to a null with potentiometer R1. If necessary, trim the R_{MATCH} value until a null is obtained. At null, read the R_{MATCH} error on the potentiometer R1 scale. Refer to Fig. 3, and make the appropriate error correction.

(1) To increase the value of R_{MATCH} by a fixed percentage, add a series resistor with a value of:

$R_{SERIES} = (R_{MATCH}/100) \times$ % error

(2) To reduce the R_{MATCH} value by a fixed percentage, add a shunt resistor with a value of:

$R_{SHUNT} = (R_{MATCH} \times 100)/$% error

Thus, a 1000-ohm resistor (nominal value) can be increased by 0.3% by adding a 3.0-ohm series resistor, or reduced by 0.3% by adding a 330-kilohm shunt resistor. When an acceptable match has been obtained on S2's ×1.0 range, repeat the process on ranges ×0.1 and ×0.01, until the match is adequate.

An alternative to this technique is to leave R1 in its midscale position and trim R_{MATCH} with R_{M2} to obtain a null on all ranges of S2.

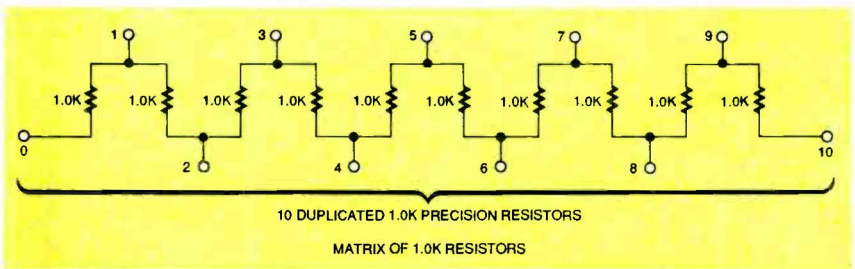

FIG. 4—THIS MATRIX OF 1-KILOHM RESISTORS yields a value equal 10 kilohms when connected in series or 100 ohms when connected in parallel.

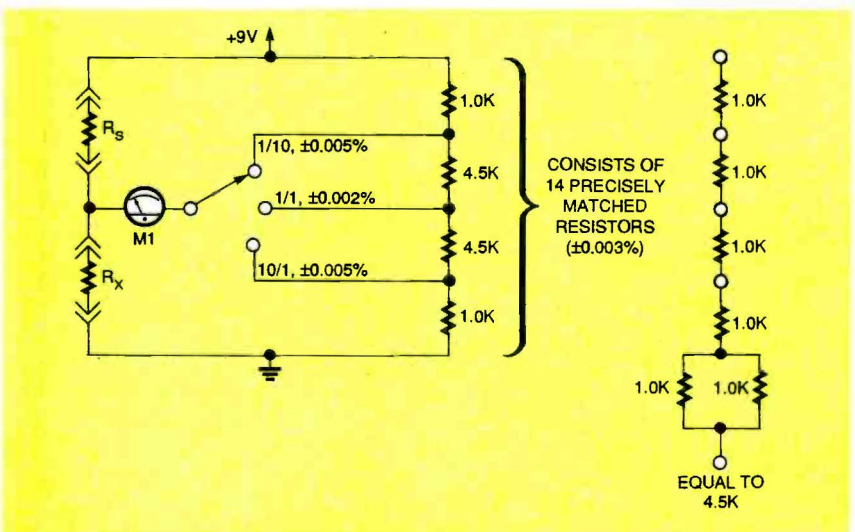

FIG. 5—CIRCUIT FOR a precision ratio-matching bridge.

Bridge applications

A precision resistor-matching bridge has many useful applications in the electronics laboratory. One of these is the duplication of precision resistor values. Figure 4 is a schematic showing how this capability can be applied. Ten identical 1-kilohm resistors are connected so that they form a series string. Together they form a resistor whose value increases in 1-kilo-

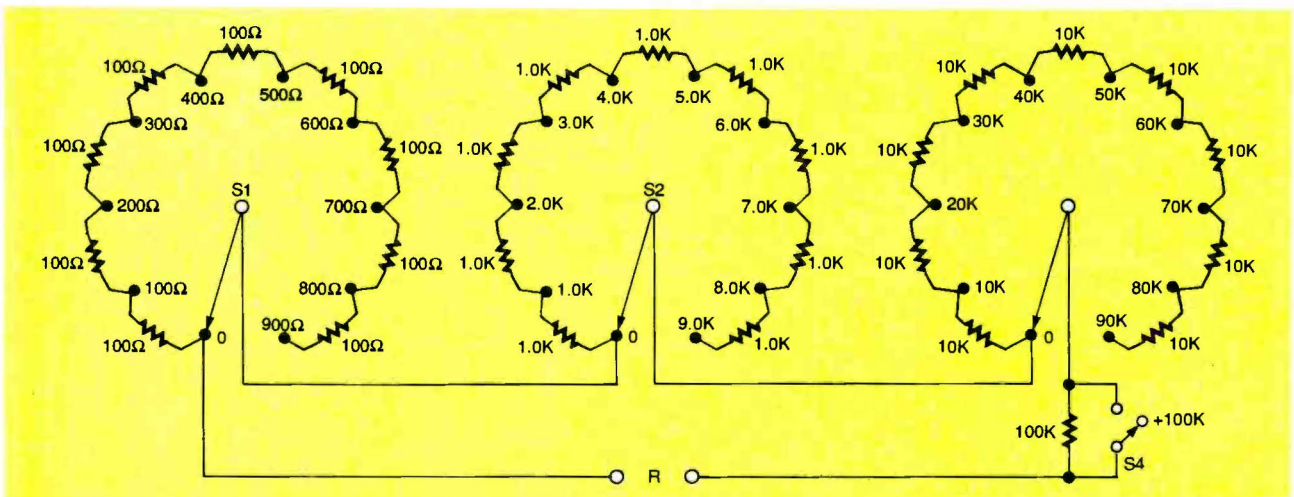

FIG. 6—THIS THREE-DECADE RESISTOR SUBSTITUTION box spans the range of 0 to 99.9 kilohms in 100-ohm steps.

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hm steps up to a maximum of 10 kilohms. If arranged in parallel, they can act as a resistor whose value decreases in steps down to 100 ohms.

It is worth noting that as more resistors are connected in parallel or series, their ±0.003% duplication errors average out and diminish. As a result, the precision of the final 10-kilohm series or 100-ohm parallel resistance is essentially equal to that of the original "master" resistor.

The actual value of the summed duplication error is equal to the original error divided by the square root of the number of summed resistors (10). In this example, it is equal to 0.001 %.

Another important application for the resistor-matching bridge application is in the formation of a precision, ratio-matching bridge, as shown in Fig 5. Here, 14 resistors are matched with a 1-kilohm (nominal) master and connected together to form a three-ratio (10/1, 1/1, and 1/10) divider.

Because all of these resistors have been precisely matched to within ±0.003 %, the ratios are defined with great precision. That value of precision is ± 0.002 % on the 1/1 range and ± 0.005% on the 10/1 and 1/10 ranges. This bridge can produce direct or decade multiple or submultiple matches with a master resistor.

If the bridge is paired with a sensitive null detector that gives a duplication precision value of 0.003%, the overall matching precision is ±0.005 % on the 1/1 range, and ±0.008 % on the 10/1 and 1/10 ranges.

Substitution boxes

Another application of the circuit shown in Fig. 5 is in matching the range and ratio arms of conventional bridges, to enhance bridge precision. Yet another is in the identification of high-precision resistors for use in decade resistor substitution boxes.

A resistance box eliminates the guesswork in determining appropriate resistance values. It facilitates circuit design, breadboarding, and the solving of circuit problems. Figure 6 is the schematic for a three-decade resistance box that spans the range of 0 to 99.9 kilohms in 100-ohm steps; 100-kilohm overranging can be obtained with switch S4.

This circuit can be made from a single precision reference resistor (1 kilohm in this example). It has many applications in the laboratory, including the calibration of bridge scales and the determination of resistor values by substitution.

A useful companion to the resistance substitution box is the multidecade capacitor substitution box. Again, like the resistance box, a capacitance box eliminates the guesswork in determining appropriate values, simplifies circuit design, breadboarding, and the solving of circuit problems. Capacitors are either selected individually or are connected in parallel to make up specific values with these boxes.

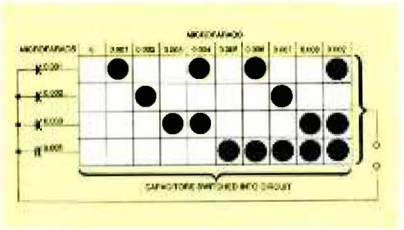

FIG. 7—THIS DECADE CAPACITOR substitution box, capable of measuring (0 to 0.009μF, is based on four capacitors and a three-pole, 10-throw switch.

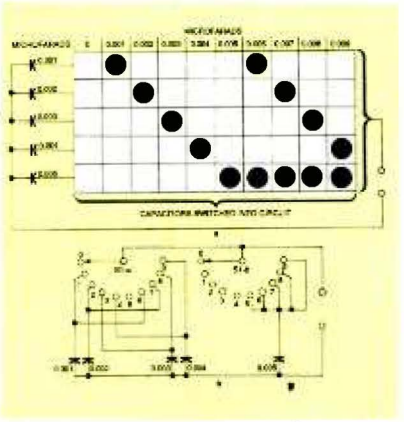

FIG. 8—A DECADE CAPACITOR matching box, organization (a) and schematic (b), can measure 0 to 0.009μF. It is based on five capacitors and a two-pole, ten-throw switch.

Figure 7 shows a capacitance box in tabular form. This is one way to organize a single-decade, 0 to 0.009 microfarad box with only four capacitors. (The 0.005-microfarad value can be made by padding up a 0.0047μF capacitor. Three capacitors must be connected in parallel to obtain the 0.009μF value. Consequently, this design calls for a three-pole, ten-throw switch.

Figure 8-a is the organization table and Fig. 8-b is the schematic for an alternative design for a 0 to 0.009μF capacitor decade substitution box. It includes five capacitors, but it requires only a two-pole, ten-throw switch. This capacitor box will cost less to build than the one shown in Fig. 7 because multideck rotary switches are more expensive than microfarad-value capacitors.

Two extra boxes based on this design will give 0.01μF and 1000.1μF steps. They can be built and connected in parallel with the circuit of Fig. 8. This combination will form a three-decade box that spans the 0 to 0.999μF range in 0.001μF steps.

Potentiometric voltmeter

Another important applica-

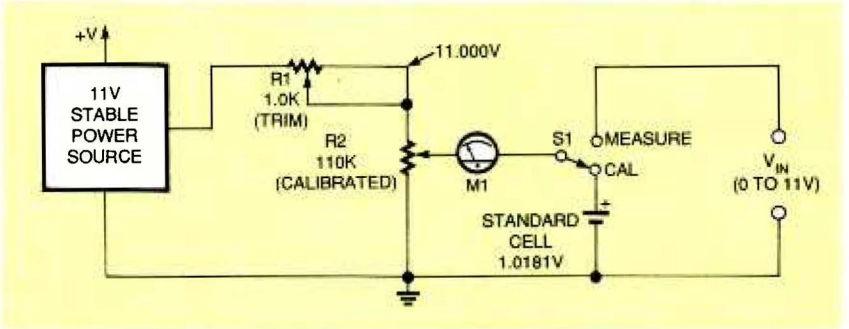

FIG. 9—SCHEMATIC FOR a potentiometric voltmeter.

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tion for the precision resistor-matching bridge is as a component of a potentiometric voltmeter, such as that shown in Fig. 9. This instrument measures DC voltages with enough precision to make it useful for calibrating the voltage scales of typical 3½ and 4½-digit digital multimeters.

The potentiometric voltmeter in Fig. 9 includes R2, a precision-calibrated 110-kilohm precision potentiometer with a scale dial. The 11.000 volts DC across this potentiometer is obtained from a stable power supply. Potentiometer R1 permits fine trimming. As a result, 0.1 millivolt passes through the resistive element for each ohm of resistance of potentiometer R2, which is accurately calibrated in terms of its output voltage.

Potentiometer R2 is used in conjunction with a primary cell that has a voltage which is accurate and constant enough to be a calibration standard for instruments. In Fig. 9, a Weston standard cell is shown. It has an output voltage of 1.018636 volts DC at 20° C.

The electrolyte of the Weston cell is a solution of cadmium sulfate. The positive electrode is a paste of mercury sulfate, and the negative electrode is made from a mixture of mercury and cadmium. The cell is housed in a pair of vertical glass tubes connected by a horizontal glass tube that forms an "H"- shaped configuration.

To make a measurement, set potentiometer R2 to read 1.0186 volts, and move S1 to the calibration (CAL) position. Trim R1 to give a zero or null reading on the meter. When this is done, the output voltages of R2 and the standard cell are equal, and precisely 11.000 volts are applied across R2.

The external DC test voltage (which must not exceed 11 volts) is then connected to the posts at the right side of the diagram, and S1 is switched to the MEASURE position. Then R2 is adjusted to give a null on meter M1. The voltage value can now be read directly from the dial scale of R2. Zero current is drawn from the test voltage at

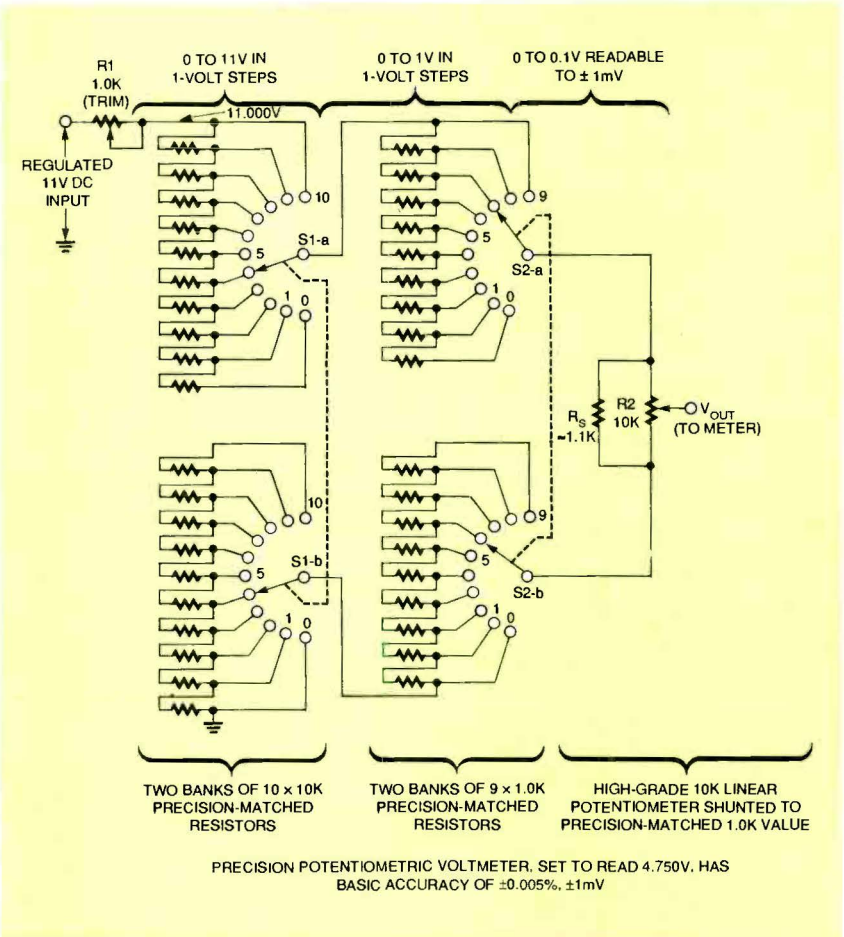

FIG. 10—THIS PRECISION POTENTIOMETRIC voltmeter, set to read 4.750 volts, has a basic accuracy of ±1.0 millivolt.

the null position. Voltages greater than 11.00 volts can be measured by applying them to the potentiometric voltmeter through a precision voltage attenuator.

Figure 10 is a circuit for the potentiometer section of the instrument shown in Fig. 9. In this precision potentiometric circuit, 110 kilohms of resistance is connected at all times, and 1 volt appears across each active 10-kilohm resistance block when 11 volts is applied to the potentiometer.

Consequently, with the wiper of S1 at contact 4, as shown, +4 volts appears on the common terminal of S1-b, and +5 volts appears on the common terminal of S1-a. These voltages are applied to the S2 resistor network. With the wiper of S2 at contact 7, there will be an output of 4.7 volts at the bottom of R2 and 4.8 volts at its top. With R2 set to its midscale, the circuit gives an output of 4.750 volts, when the controls are set as described.

The circuit in Fig. 10 can only read voltages to within the nearest 1 millivolt, so the initial calibration reading must be set to 1.0186 volts when the standard cell is in the circuit. An additional decade can be added to the circuit by replacing R2, and its associated components with a duplicate of the S2 and R2 related circuitry (i.e., all the circuitry to the right of S1). However, all resistor values must be reduced by a factor of ten.

This modification permits the potentiometric voltmeter to measure voltages to within the nearest 0.1 millivolt, and it permits the circuit to be calibrated initially to 1.0186 volts. All resistors in the voltmeter circuit must be precisely matched against a single 10-kilohm reference resistor. Ω

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